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Validation of three-dimensional hydrodynamic models in the Gulf of Finland based on a statistical analysis of a six-model ensemble

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ABSTRACT

Six three-dimensional hydrodynamic models were compared in their simulations of the hydrographic features of the Gulf of Finland in the Baltic Sea in the summer-autumn period of 1996. Validation was undertaken using more than 300 vertical hydrographic profiles of salinity and temperature. The analysis of model performance, including ensemble averaging of the results, was undertaken with a view to assessing the potential utility of the models in reproducing the physics of the Baltic Sea accurately enough to serve as a basis for accurate simulations of biogeochemistry once ecosystem models are incorporated.

The overall performance of the models was generally satisfactory. However, the comparison between observations and ensemble simulations indicated some drawbacks in the parameterization of vertical mixing. Also the choice of initial conditions, surface forcing and differences between real topography and that one used in the models influenced the differences between observations and model results. Looking from another perspective we can state that the accuracy of the present hydrodynamic models determines the upper limit for that of ecosystem models. In turn, the reliability of the hydrodynamic models depends on the physical forcing which is not always as accurate as one may expect. In the future further development of hydrodynamic models is needed in the following areas: the description of vertical mixing and advection should be improved, description of forcing functions including bathymetry, atmospheric forcing, river discharge and boundary conditions should be refined. Additionally more work should be focused on model inter comparisons to clarify the reasons behind the differences in between the models and between model and data

Keywords: Baltic Sea, hydrodynamics, modeling, inter-comparison, statistical analysis

1. Introduction

Eutrophication represents the most common environmental problem confronting the current Baltic Sea ecosystem. The problem is complicated by the special topographic and hydrographic features of this estuarial sea resulting in natural variations comparable to anthropogenic impact. Although symptoms of the Baltic Sea eutrophication are now well documented and qualitatively understood, the quantitative description of many important interactions and phenomena is much weaker or hardly exists.

To implement an ensemble of mathematical models as a tool for better quantitative description of Baltic Sea eutrophication necessary to increase confidence in scenario simulations of the expensive nutrient load reduction measures. The objective was achieved through the following tasks in the project Eutrophication-Maps (Ensemble Model simulations as a tool to study the Baltic Sea and the Gulf of Finland eutrophication):

By:

- validating and estimating reliability of the hydrodynamic models by comparisons to observations and between themselves

- using ensemble of models to simulate ecological state of the Baltic Sea for the period 1995-2000

This paper is devoted to investigate the results of the first part of the project -an intercomparison of the results of six hydrodynamic models.

2. Material and methods

The following models participated to the intercomparison (see Table 1 for details)

1. Operational model HIROMB of the Swedish Meteorological and Hydrological Institute (Funkquist, 2001).

2) OAAS-model developed by Oleg Andrejev and Alexander Sokolov (Andrejev and Sokolov, 1989; Sokolov et al., 1997; Andrejev et al., 2004a,b, hereafter denoted as OAAS). The model has now been applied to operational forecasting in the Finnish Institute of Marine Research (FIMR). The model is also used in Stockholm University and in State Oceanographic Institute, Russia.

3) SPBM-model developed by Ivan Neelov (Neelov, 1982, Neelov et al., 2003) in St.Petersburg Branch, P.P.Shirshov Institute of Oceanology, the Russian Academy of Sciences and recently used by a consortium of St.Petersburg Institutes.

4) EIA-model (Simons, 1980; Inkala and Myrberg, 2002) developed and exploited in the Environmental Impact Assessment Centre of Finland Ltd. (EIA).

5) COHERENS-model (Luyten P. J. et al., 1999). The model has been implemented for the Baltic Sea at the National Environmental Research Institute (NERI) in Denmark and currently exploited by NERI and Finnish Environment Institute (SYKE).

6) MIKE3-model (DHI Water and Environment, 2000) developed in the DHI and exploited by DHI and the Marine Systems Institute (MSI) in Estonia.

Table 1. The basic features of hydrodynamic modules of participating models

Model ID	**HIROMB**	**OAAS**	**SPBM**	**EIA**	**COHERENS**	**MIKE3**
Horizontal grid and resolution	**Spherical** Arakawa C grid, 4´×2´	Spherical, Arakawa C grid, 4´×2´	Spherical Arakawa B grid, 4´×2´	Spherical Arakawa C grid, 4´×2´	Spherical, **Arakawa C grid, 4'x2'**	Spherical, Arakawa C grid, 4´×2´
Vertical grid and resolution	z-coordinate 78 levels min dz=2m	z-coordinate 78 levels min dz=2m	z-coordinate 78 levels min dz=2m	z-coordinate 20 levels min dz=2.5m	σ-coordinate 50 levels	z-coordinate 120 levels min dz=2 m
Vertical turbulence scheme	*k-ω* model	Kochergin scheme (1987)	*k-l* model	*k-ε* model	*k-ε* model	*k-ε* model
Horizontal turbulence scheme for	Smago-rinsky (1963)	Smago-rinsky (1963)	Smago-rinsky (1963)	Smago-rinsky (1963)	none	Smago-rinsky (1963)

momentum						
Horizontal turbulence scheme for T and S	Smago-rinsky (1963)	Smago-rinsky (1963)	K_l=const= 10^6 cm^2s^{-1}	none	none	Smago-rinsky (1963)
Advection scheme for momentum	Conservati-ve and fully 3D scheme, based on Zalesak	Upwind scheme	3d order scheme (Fujii and Obayashi , 1989)	TVD-superbee scheme	upwind scheme	3d order scheme QUICKEST (Vested et al., 1992)
Advection scheme for tracers (T, S and others)	Conservati-ve and fully 3D scheme, based on Zalesak	TVD-superbee scheme	3d order scheme (Fujii and Obayashi , 1989)	TVD-superbee scheme	TVD-superbee scheme	3d order scheme QUICKEST (Vested et al., 1992)
Convection	Hydrostatic model, convective adjustment	Hydrostatic model, convective adjustment	Hydrostatic model, no convective adjustment	Hydrostatic model, no convective adjustment	Hydrostatic model, convective adjustment	Non-hydrostatic model
Equation of state	UNESCO (1981)	Millero and Kremling (1976)	Millero and Kremling (1976)	UNESCO (1981)	UNESCO (1981)	UNESCO (1981)
Sea surface heat fluxes: 1)Short-wave radiation	Shane (1984)	Rosati and Miyakoda (1988)	Zillmann (1972)	Kennedy (1944), Klein (1948)	Luyten et al. (1999)	Reed (1997)
2) Long-wave radiation	Idso and Jackson (1969)	Gill(1982)	Berlyand(1956)	Iziomon et al. (2003)	Luyten et al. (1999)	Brunt(1929)
3)Sensible heat flux	Liu et al. (1979)	Luyten et al. (1999)	Bulk formulation, C_D = 1.75 10^{-3}	Bowen (1926)	Luyten et al. (1999)	Bulk formulation, C_D = 1.41 10^{-3}
4)Latent heat flux	Liu et al. (1979)	Luyten et al. (1999)	Bulk formulation	Marciano and Harbeck (1954)	Luyten et al. (1999)	Bulk formulation

The models have common setup in terms of the initial and boundary conditions and forcing fields (Table 2), while the internal implementation of the models is different. The ensemble contains only one non–hydrostatic model (MIKE3). In the hydrostatic models, the convection is parameterized via the mechanism of convective adjustment or, generally, is not specially considered. Five models use z-coordinate in vertical while COHERENS uses σ-coordinate. Models differ by vertical resolution, vertical turbulence scheme, approximation of advective terms, parameterizations of heat fluxes at the sea surface, and even the equation of state. For multi-year simulations the inclusion of ice dynamics is essential, but it is not of major importance as in the present case our model simulations cover the ice-free period in the GoF and we analyze the results from time interval of summer-autumn only.

Table 2. Conditions for the short-period simulation: bathymetry, forcing, boundary and initial conditions for the whole Baltic Sea

Parameter	Short description	Time period	Data source
Sea depth	Depths on the grid 4´×2´ with the left lower corner having coordinates 53.8°N, 9.45°E	n/a	Seifert and Kayser(1995)
Atmospheric forcing (wind velocity, air temperature, relative humidity, cloudiness, precipitation, pressure)	SMHI reanalysis, temporal resolution 3h, spatial resolution 1°	1.04.1996-31.10.1996	Krister Boqvist (personal communication)
River discharge	Monthly mean values for Baltic Sea rivers	Climatic data	Bergstöm and Carlsson (1994)
Conditions for salinity and temperature in river mouths: $S=0$, zero heat flux in all rivers excepting Neva, $T=T(t)$ in Neva	Temperature values in Neva averaged over 10-days period	1.04.1996-31.10.1996	Valery Tsepelev (personal communication)
Boundary conditions in Danish Straits: current velocity(U,V), temperature T, salinity S	Model results for one grid point of 75m depth, temporal resolution 3h, 11 levels with min dz=4m	1.04.1996-31.10.1996	Results of HIROMB, prepared by L.Funkquist
Initial conditions: temperature T, salinity S, zero values for: current velocity, sea level, ice thickness and concentration	Averaged values for wintertime period (January- March) of two years: 1995-96	1.04.1996	Baltic Environment Database at Stockholm University (BED, 1990)

Set-up of simulations

A period from April 1 to November 1, 1996 was simulated using the ensemble of models. Initial distributions of temperature and salinity fields in the Baltic Sea (these distributions in the GoF are shown in Figs.2, 7a, 8a) were constructed from the data available in the Baltic Environmental Database (BED, Sokolov et al. 1997) for 3 wintertime months (January –March) of two consecutive years (1995-96). The usage of data for two 3-month periods led to satisfactory coverage of the Baltic Sea area by data and hence reasonable presentation of these initial fields is available (in the case of using only 1996 data, some parts of the Baltic Sea, including the GoF, had “white spots” without any data).

The meteorological forcing (wind speed and -direction, air temperature, relative humidity, cloudiness and precipitation) was taken from the SMHI gridded data (Krister Boqvist, SMHI, see Table 2). Preliminary analysis of these data showed that the geostrophic wind velocity fields contain some unrealistically high values. They have been rejected in such way that wind speeds exceeding 40m/s were taken to be equal to this maximum value. From the geostrophic wind, the near-surface wind (10 m) was calculated by a standard procedure by multiplying the wind speed by 0.6 and turning the wind direction 15 degrees to the left (Bo Gustafsson, personal communication). Precipitation is accounted for in all models except HIROMB where precipitation is taken to be equal to evaporation.

Monthly mean river discharges were obtained from Bergstrom and Carlsson (1994). Test runs showed, that prescribing usual “no heat flux” condition at the mouth of Neva leads to high water temperatures in the Neva Bay and in the easternmost part GoF. To overcome the discrepancy, the water temperature in Neva was prescribed using available observational data. “No-heat flux” condition was kept for the other rivers.

The boundary conditions for the open boundary in the Danish Straits were prescribed from model results of HIROMB rather than using scarce data (Table 2).

Data for comparison and methods for evaluating model skills

During the implementation of our inter-comparison data set, output for every model has been produced on a unified grid. The grid coincides in horizontal plane with a sea depth grid (see Table 2) and has 50 levels in the upper 100-meter layer with dz=2m starting from z_1=1m up to z_{50}=99m and 27 levels below with dz=5m, z_{51}=102.5m, z_{52}=107.5m, …, z_{77}=232.5m. Model outputs are preprocessed so that three-dimensional distributions of water temperature T and salinity S are averaged over time interval τ = 5 days for the period from June 1 to November 1 in the GoF.

Observation data on temperature and salinity for the Gulf of Finland in 1996, used for comparison with model results, includes both satellite and ship data (Table 3). All available data of ship observations were placed into a special database.

Table 3. Observation data for the Gulf of Finland in 1996 used for comparison with model results

Parameter	Short description	Time period	Data source
Sea surface temperature(SST*)*	infrared and microwave derived SSTs with spatial resolution of ?km and daily temporal resolution	01.06 -31.08.1996	NASA, PODAAC (Physical Oceanography Distributed Active Archive Center)
Ship data combined into a special database			
Temperature and salinity (inventoried in BED)	Stations performed in the GoF	01.06 -31.10.1996	BED
Temperature and salinity (not inventoried in BED)	4 Finnish coastal stations of intensive monitoring (Haapasaari, Huovari, Längden, Länsi-Tonttu)	01.05-30.11.1996	SYKE
Temperature and salinity (not inventoried in BED)	Russian stations performed in the eastern GoF	01.06 -31.10.1996	Russian State Hydrometeorological University, Russian North-West Hydrometeorological Service

As a first step of model verification visual comparison is performed using all available data. The above database was used to build observed sea-surface and bottom maps of temperature and salinity in the Gulf, vertical temperature and salinity sections across and along the Gulf, time-depth plots of temperature and salinity locations of three (from four) Finnish intensive monitoring stations (SYKE) at which were enough data for adequate presentation of seasonal evolution of temperature and salinity. In this study the data were averaged over certain periods to get a better spatial coverage in the region under investigation. Sea-surface temperature (SST) distributions for 5-day periods were also obtained from daily mean SST derived from satellite measurements (PODAAS). Besides of comparing each model result with data model ensemble mean values were calculated. In this study the ensemble averaging has been performed only for those cases when large enough data sets are available to produce reliable plots or curves for comparison.

A statistical analysis of the differences between the model outputs and data have been performed for 3 groups of detailed vertical profiles of temperature and salinity : 1) all available R/V “Aranda” CTD-data (Finnish Institute of Marine Research) collected in the western GoF in late June-early July; 2) R/V “Aranda” CTD-data collected in the western GoF in the mid-July (Fig.1, the upper panel), and 3) the R/V ”Nikolay Matusevich” CTD-data collected in the eastern GoF also in mid-July (Fig.1, the middle panel). Other available data (from BED and from SYKE intensive monitoring stations) have been excluded from the statistical analysis because at these stations the measurements were performed at standard depth, i.e. with a rather low vertical resolution. Length of corresponding data series of these vertical profiles were not long enough providing a low level of sampling significance.

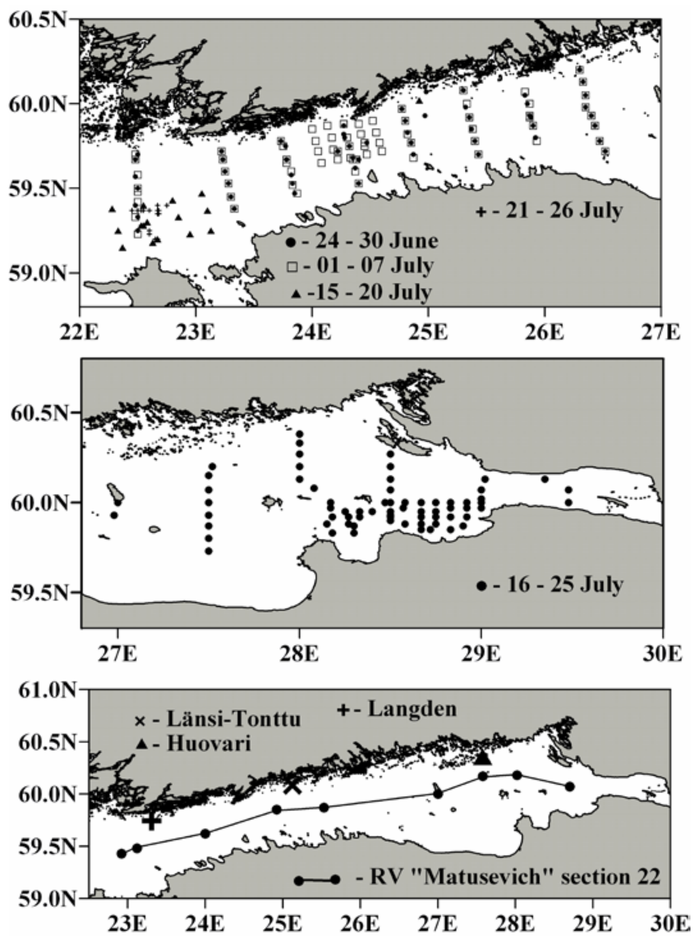

Fig.1. (a) Locations of R/V "Aranda" stations performed in the western GoF in June-July, 1996; (b) Locations of R/V "Matusevich" stations performed in the eastern GoF in July 16-25, 1996; (c) the section along the GoF performed by R/V "Nikolay Matusevich" in August 11-12, 1996; the crosses are the locations of SYKE intensive monitoring station Huovari (60°23.30′ N, 27°39.49′ E), Länsi-Tonttu (60°04.99' N, 25°07.39' E), Längden(59°46.60′ N, 23°15.98′ E).

3. Results

An few examples is given here for results by calculated by six different models, that from measurements and an ensemble mean of the results of six models.

Lets look at the bottom salinity:

The distinctive feature of the observed near-bottom salinity distribution averaged over the June-August period is a tongue of high salinity penetrating into the central part of the Gulf from the Baltic Proper (Fig. 2). Starting from 8.5-9.0 ‰ at the entrance in the GoF, salinity values in this tongue are still high (7.0-7.5 ‰) at 27.5°E. Eastward of that longitude the Gulf is getting shallower and there is no specific bottom layer separated from upper layer by a halocline. All the models describe well the penetration of the salt water tongue until the longitude 27.5, the best being MIKE3. However, the salinity according to the models is not so high as the observed 7 ‰ at the above-mentioned longitude: the models usually give an underestimation of salinity by 0.5-1 ‰. Thus, the modelled salinity stratification is somewhat weaker than the observed one. It seems to be so that MIKE and HIROMB show the best performance concerning estuarine circulation. However, the model description of eastuarine circulation has some drawbacks. Westward transport of fresh water in the upper layer and eastward transport of saline water is underestimated by the models. A possible explanation of the differences in bottom salinity between the model and the measurements here is the fact that the grid-approximation of depths used by the models is somewhat shallower than the real ones. Also the near-bottom salinity near the entrance of the GoF is simulated rather well by the models, but somewhat underestimated by SPB (by 0.5 ‰), COHERENS (by 0.5 ‰) and EIA (by 1.0 ‰). Fig. 2 shows the difference between measurements and averaged distribution of the results of all the six models (ensemble mean). The models' performance is fairly good because the difference is usually 0.5-1 ‰ in the open Gulf. Larger differences are found only at the coastal regions where the model depth and the real depth differ significantly from each others. The number of data at the coastal zone is not always large enough to describe realistically the salinity distribution.

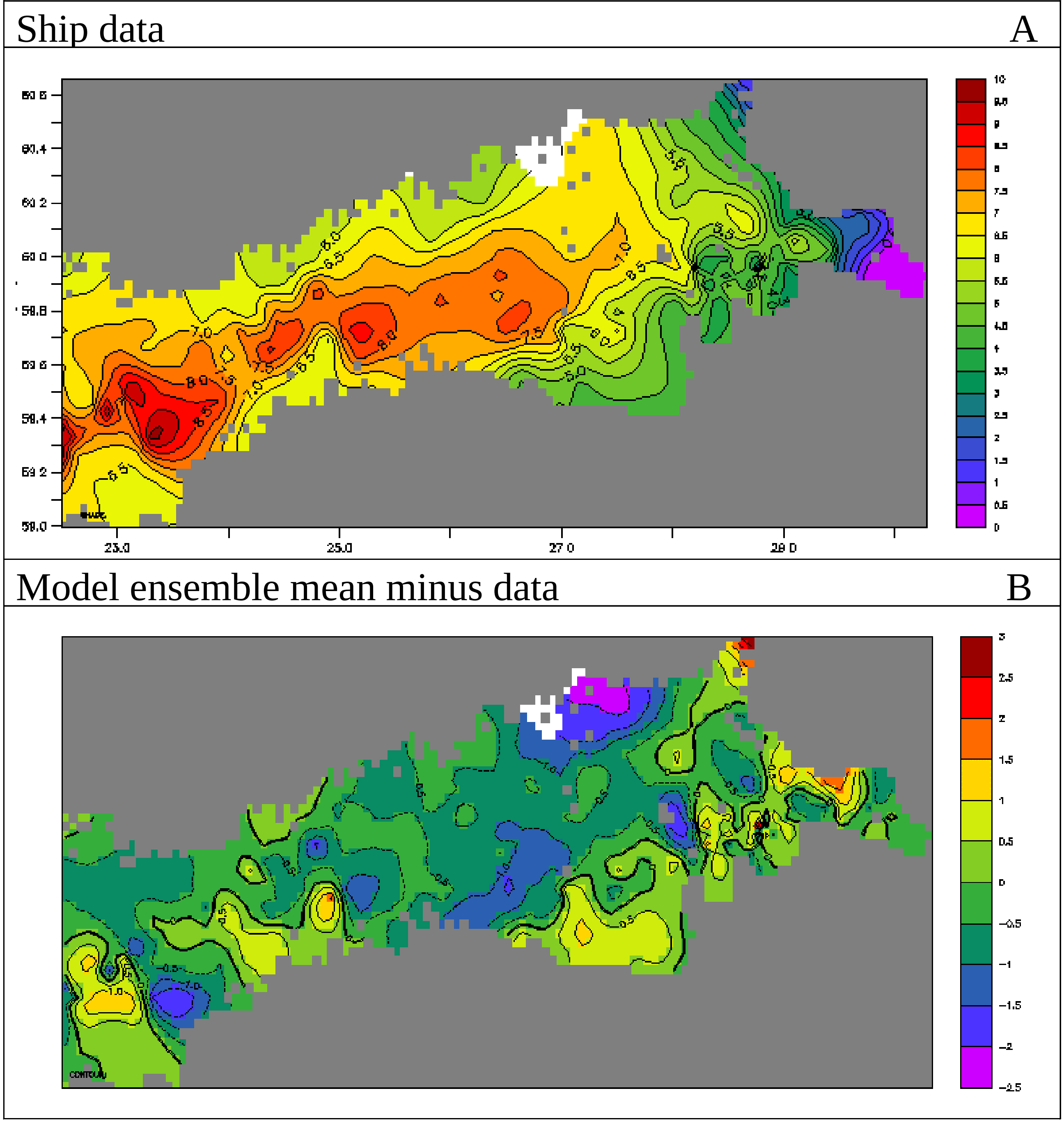

Fig.2. The near-bottom salinity (‰) in the Gulf of Finland averaged over the period from June 1 to September 1, 1996 according to A) Ship data, B) Difference between ensemble mean of the models and data

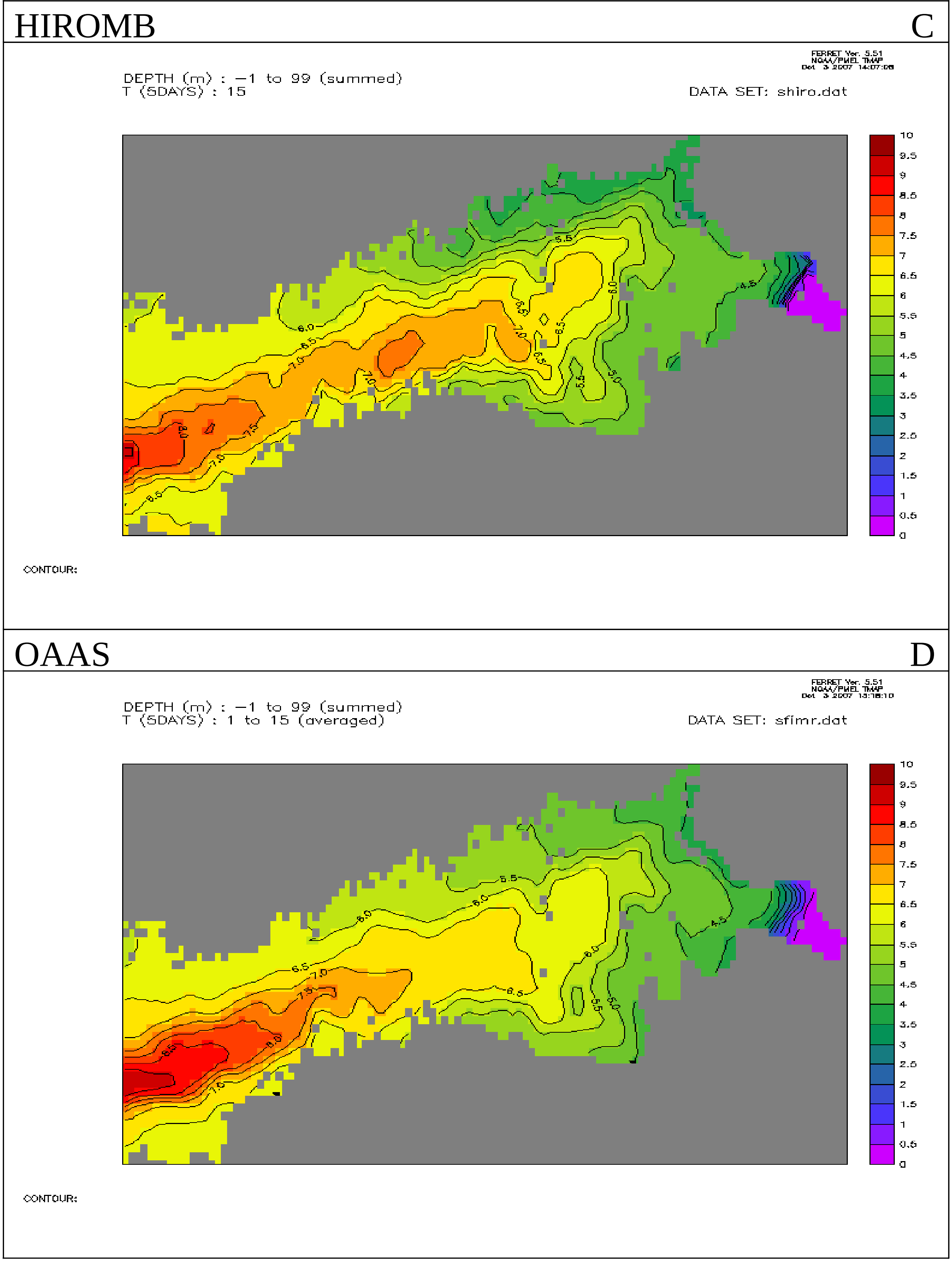

Fig.2. The near-bottom salinity (‰) in the Gulf of Finland averaged over the period from June 1 to September 1, 1996 according to C) HIROMB, D) OAAS .

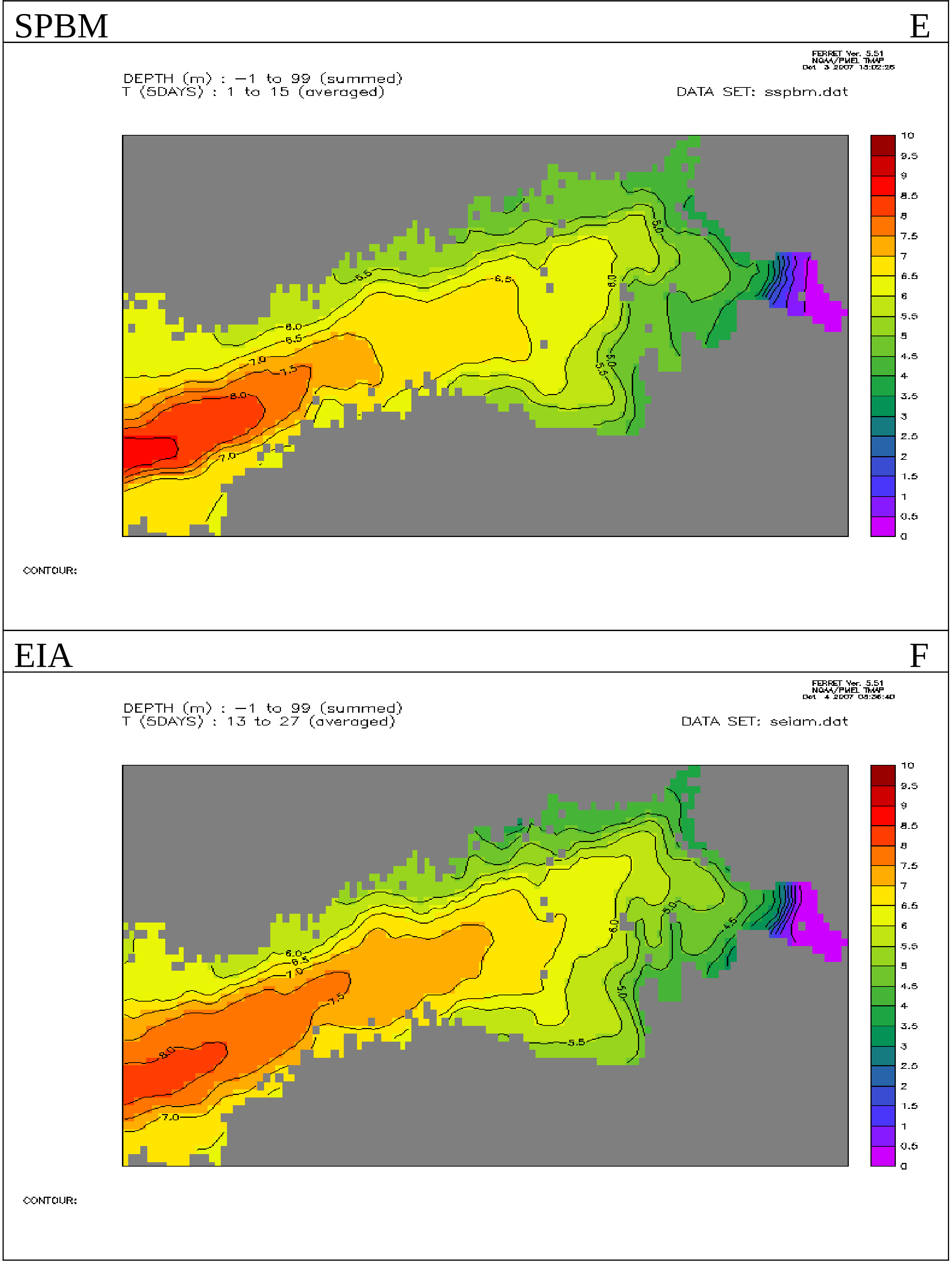

Fig.2. The near-bottom salinity (‰) in the Gulf of Finland averaged over the period from June 1 to September 1, 1996 according to E) SPBM, F) EIA.

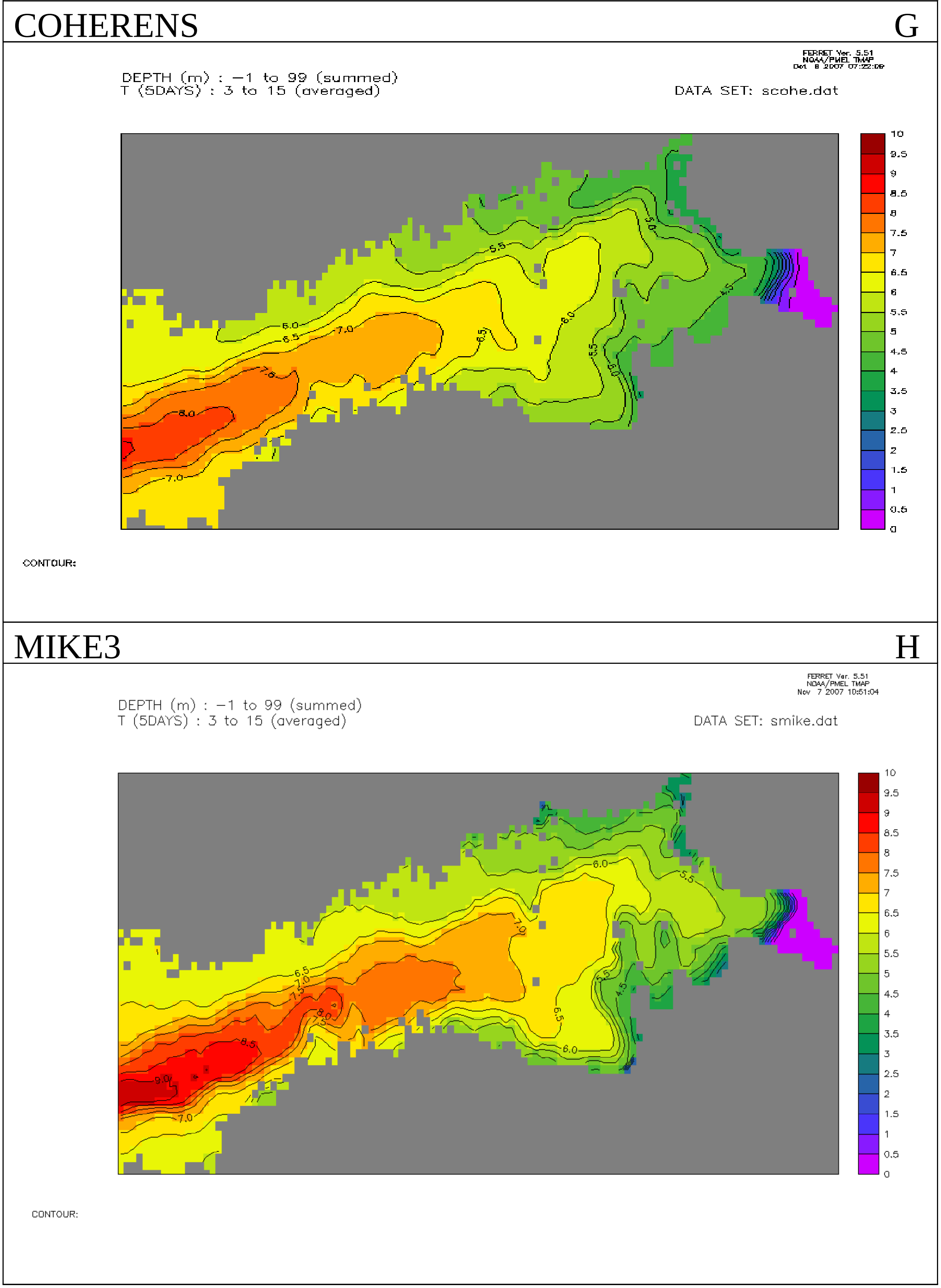

Fig.2. The near-bottom salinity (‰) in the Gulf of Finland averaged over the period from June 1 to September 1, 1996 according to G) COHERENS, H) MIKE3.

Statistical analysis

The statistical analysis for temperature showed that the models' performance was in general better in the western part of the gulf than in the eastern (Table 4). The correlation coefficients in the west were usually higher than 0.9 whereas values were lower than 0.9 for the eastern gulf. The MIKE3 model falls out of ensemble during the second period in the western gulf due to artificially strong upwelling produced by the model. Even considering the models performance in the western Gulf during two consecutive periods we may conclude that different models give better coincidence with data for different periods. For instance, the HIROMB being among the worst between June 24 and July 4, the model gives the best statistical characteristics for the next period, July 15-26. Except of correlation coefficients and the fact that several profiles were excluded from the analysis in the eastern GoF, the results in terms of other statistical characteristics are comparable for the eastern and western Gulf. In general, the results of different models for different time periods can be combined to estimate the temperature in the GoF with RMSE less than 2°C.

Table 4. Statistical characteristics for temperature in the western and eastern Gulf of Finland

Model	Correlation coefficient	Mean absolute error,°C	Root mean square error,°C	Spread,°C
The western Gulf of Finland, June 24 – July 4, 1996, 172 profiles of R/V "Aranda"				
HIROMB	0.86	2.05	2.64	1.92
OAAS	0.95	1.16	1.55	1.19
SPBM	0.93	1.19	1.52	1.22
EIA	0.92	1.70	2.03	1.57
COHERENS	0.95	1.06	1.39	1.18
MIKE3	0.87	2.11	2.62	1.81
The western Gulf of Finland, July 15-26, 1996, 41 profiles of R/V "Aranda"				
HIROMB	0.96	1.49	1.85	1.22
OAAS	0.89	2.16	2.77	1.88
SPBM	0.92	1.92	2.46	1.64
EIA	0.94	1.59	1.85	1.40
COHERENS	0.92	1.67	2.10	1.62
MIKE3	0.74	3.34	4.38	3.38

The eastern Gulf of Finland, July 16-25, 1996, 69 profiles of R/V "Matusevich"				
HIROMB	0.91	1.28	1.52	0.97
OAAS	0.82	1.92	2.20	1.28
SPBM	0.84	2.08	2.20	0.98
EIA	0.72	1.76	1.95	1.65
COHERENS	0.81	1.56	1.94	1.39
MIKE3	0.80	3.62	4.30	3.82

4. Summary

The six different models perform reasonably for the short term run (April-November 1996). Model runs of the different models have been carried out under the same initial and boundary conditions and external atmospheric forcing. The analysis of the hydrodynamic components of the ecosystem models has been focused on the Gulf of Finland. Deviations from mean temperatures are generally less than 1-2°C. The mean error in salinity is less than 1 PSU. Taking ensembles averages of the different models improve the results, i.e. models show no general over- or underestimation of hydrodynamic parameters. Although sophisticated turbulence closure schemes has been applied, the main uncertainty of all models is the correct simulation of the mixed layer dynamics including correct depths and sharpness of the corresponding thermo- and haloclines. Eutrophication-Maps project has shown that ecosystem models of the Baltic Sea need high horizontal (order of the internal Rossby-radius) and vertical resolution (meters) to resolve the complex dynamics and topography of the Baltic Sea.

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